MODULATORS FOR RESONANT OPTICAL POWER CONTROL DEVICES AND METHODS OF FABRICATION AND USE THEREOF

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FIELD OF THE INVENTION

The field of the present invention relates to devices for modulating optical power transmission through optical fiber. In particular, apparatus, methods of use, and methods of fabrication of resonant optical power control devices are described herein for modulating optical power transmission through a fiber-optic waveguide using a modulator element coupled to a whispering-gallery-mode optical resonator in turn coupled to the fiber-optic waveguide.

BACKGROUND

This application is related to subject matter disclosed in:

A1) U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic modulator" filed 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A2) U.S. Application No. 09/454,719 entitled "Resonant optical wave power control devices and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said application being hereby incorporated by reference in its entirety as if fully set forth herein;

A3) U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-microsphere coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A4) U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said

application being hereby incorporated by reference in its entirety as if fully set forth herein; and

A5) U.S. provisional Application No. 60/183,499 entitled "Resonant optical power control devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C. Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

A6) U.S. provisional application entitled "Fiber-optic waveguides for evanescent optical coupling and methods of fabrication and use thereof", filed 08/18/2000 in the names of Peter C. Sercel, Guido Hunziker, and Robert B. Lee, Application No. 60/226,147, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

A7) U.S. provisional application entitled "Waveguides and resonators for integrated optical devices and methods of fabrication and use thereof", filed concurrently with the present application in the name of Oskar J. Painter, Application No. not yet assigned, said provisional application being hereby incorporated by reference as if fully set forth herein.

A8) U.S. provisional Application No. 60/170,074 entitled "Optical routing/switching based on control of waveguide-ring resonator coupling", filed 12/09/1999 in the name of Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

A9) U. S. Pat. No. 6,052,495 entitled "Resonator modulators and wavelength routing switches" issued 04/18/2000 in the names of Brent E. Little, James S. Foresi, and Hermann A. Haus, said patent being hereby incorporated by reference in its entirety as if fully set forth herein.

A10) U. S. Pat. No. 6,101,300 entitled "High efficiency channel drop filter with absorption induced on/off switching and modulation" issued 08/08/2000 in the names of Shanhui Fan, Pierre R. Villeneuve, John D. Joannopoulos, Brent E. Little, and Hermann A. Haus, said patent being hereby incorporated by reference in its entirety as if fully set forth herein.

This application is also related to subject matter disclosed in the following 31 publications, each of said 31 publications being hereby incorporated by reference in its entirety as if fully set forth herein:

P1) Ming Cai, Guido Hunziker, and Kerry Vahala, "Fiber-optic add-drop device based on a silica microsphere whispering gallery mode system", IEEE Photonics Technology Letters Vol. 11 686 (1999);

P2) J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phased-matched excitation of whispering gallery-mode resonances by a fiber taper", Optics Letters Vol. 22 1129 (1997);

P3) R. D. Pechstedt, P. St. J. Russell, T. A. Birks, and F. D. Lloyd-Lucas, "Selective coupling of fiber modes with use of surface-guided Bloch modes supported by dielctric multilayer stacks", J. Opt. Soc. Am. A Vol. 12(12) 2655 (1995).

P4) R. D. Pechstedt, P. St. J. Russell, " Narrow-band in-line fiber filter using surface-guided Bloch modes supported by dielectric multilayer stacks", J. Lightwave Tech. Vol. 14(6) 1541 (1996).

P5) Hiroshi Wada, Takeshi Kamijoh, and Yoh Ogawa, " Direct bonding of InP to different materials for optical devices", Proceedings of the third international symposium on semiconductor wafer bonding: Physics and applications, Electrochemical Society Proceedings, Princeton NJ, Vol. 95-7, 579 –591 (1995).

P6) R. H. Horng, D. S. Wuu, S.C. Wei, M. F. Huang, K.H. Chang, P.H. Liu, and K. C. Lin, "AlGaInP/AuBe/glass light emitting diodes fabricated by wafer-bonding technology", Appl. Phys. Letts. Vol. 75(2) 154 (1999).

P7) Y. Shi, C. Zheng,H. Zhang, J.H. Bechtel, L.R. Dalton, B.B. Robinson, W. Steier, "Low (sub-1-volt) halfwave voltage polymeric electro-optic modulators achieved by controlling chromophore shape", Science Vol. 288, 119 (2000).

P8) E. L. Wooten, K.M. Kissa, and A. Yi-Yan, "A review of lithium niobate modulators for fiber-optic communications systems", IEEE J. Selected Topics in Quantum Electronics, Vol. 6(1), 69 (2000).

P9) D.L. Huffaker, H. Deng, Q. Deng, and D.G. Deppe, “Ring and stripe oxide-confined vertical-cavity surface-emitting lasers”, Appl. Phys. Lett., Vol. 69(23), 3477 (1996).

P10) Serpenguzel, S. Arnold, and G. Griffel, “Excitation of resonances of microspheres on an optical fiber”, Opt. Lett. Vol. 20, 654 (1995);

P11) F. Treussart, N. Dubreil, J. C. Knight, V. Sandoghar, J. Hare, V. Lefevre-Seguin, J. M. Raimond, and S. Haroche, “Microlasers based on silica microspheres”, Ann. Telecommun. Vol. 52, 557 (1997); and

P12) M. L. Gorodetsky, A. A. Savchenkov, V. S. Ilchenko, “Ultimate Q of optical microsphere resonators”, Optics Letters, Vol. 21, 453 (1996).

P13) Carl Arft, Diego R. Yankelovich, Andre Knoesen, Erji Mao, and James S. Harris Jr., “In-line fiber evanescent field electrooptic modulators”, Journal of Nonlinear Optical Physics and Materials Vol. 9(1) 79 (2000).

P14) Pochi Yeh, Amnon Yariv, and Chi-Shain Hong, “Electromagnetic propagation in periodic stratified media. I. General theory”, J. Optical Soc. Am., Vol. 67(4) 423 (1977).

P15) Ming Cai, Oskar Painter, and Kerry J. Vahala, “Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system”, Physical Review Letters, Vol. 85(1) 74 (2000).

P16) M. Kondow, T. Kitatani, S. Nakatsuka, M. C. Larson, K. Nakahara, Y. Yazawa, M. Okai, and K. Uomi, “GaInNAs: A novel material for long-wavelength semiconductor lasers”, IEEE Journal of Selected Topics in Quantum Electronics, Vol 3(3), 719 (1997).

P17) H. Saito, T. Makimoto, and N. Kobayashi, “MOVPE growth of strained InGaAsN/GaAs quantum wells”, J. Crystal Growth, Vol. 195 416 (1998).

P18) W. G. Bi and C. W. Tu, “Bowing parameter of the band-gap energy of GaN_xAs_{1-x}”, Appl. Phys. Lett. Vol. 70(12) 1608 (1997).

P19) H. P. Xin and C. W. Tu, “GaInNAs/GaAs multiple quantum wells grown by gas-source molecular beam epitaxy”, Appl. Phys Lett. Vol. 72(19) 2442 (1998).

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P30) E. I. Chen, N. Holonyak, Jr., andM. J. Ries, "Planar disorder- and native-oxide-defined photopumped AlAs-GaAs superlattice minidisk lasers", J. Appl. Phys. Vol. 79(11) 8204 (1996).

P31) Y. Luo, D. C. Hall, L. Kou, L. Steingart, J. H. Jackson, O. Blum, and H. Hou, "Oxidized $Al_xGa_{1-x}As$ heterostructures planar waveguides", Appl. Phys. Lett. Vol. 75(20) 3078 (1999).

Optical fiber and propagation of high-data-rate optical pulse trains therethrough has become the technology of choice for high speed telecommunications. Wavelength division multiplexing (WDM) techniques are now commonly used to independently transmit a plurality of signals over a single optical fiber, independent data streams being carried by optical modes propagating through the optical fiber at a slightly differing optical carrier wavelengths. A propagating mode of a particular wavelength must be modulated, independently of other propagating wavelengths, in order to carry a signal. A signal carried by a particular wavelength channel must be independently accessible for routing from a particular source to a particular destination. These requirements have previously required complex and difficult-to-manufacture modulating and switching devices requiring extensive active alignment procedures during fabrication/assembly, and as a result are quite expensive. Such devices may require conversion of the optical signals to electronic signals and/or vice versa, which is quite power consuming and inefficient. In the patent applications A1 through A6 cited above a new approach has been disclosed for controlling optical power transmitted through an optical fiber that relies on the use of resonant whispering-gallery-mode (hereinafter "WGM") optical resonators, or other optical resonators, for direct optical coupling to a propagating mode of an optical fiber resonant with the optical resonator, thereby enabling wavelength-specific modulation of optical signals propagating through the optical fiber. A thorough discussion of the features and advantages of such optical power control devices and techniques, as well as methods of fabrication, may be found in these applications, already incorporated by reference herein.

A primary design goal of fiber optic communications has been that, to the greatest extent feasible, components and/or devices should keep the light wave signal in optical fiber. This is based on the common sense observation that to couple light from a device into optical fiber or vice versa is very expensive to implement and typically introduces undesirable loss. Fiber Bragg filters and erbium fiber optical amplifiers are technologies that exemplify successful realizations of the goal. Other examples more directly relevant to this disclosure are optical power control devices, including all-fiber-optic modulators and/or all-fiber channel add-drop filters (described in the patent applications A1 through A8 cited hereinabove and incorporated by reference herein). One important element of these latter devices is optical coupling between a fiber-optic waveguide and a whispering-gallery-mode optical resonator. The WGM optical resonator provides wavelength specificity, since only propagating optical modes substantially resonant with the WGM optical resonator will be significantly affected by the device. A fiber-optic waveguide for transmitting the optical signal through the control device is typically provided with an evanescent optical coupling segment, where an evanescent portion of the propagating optical mode extends beyond the waveguide and overlaps a portion of a whispering-gallery optical mode of the WGM optical resonator, thereby optically coupling the WGM optical resonator and the fiber-optic waveguide. The evanescent optical coupling segment may take one of several forms, including an optical fiber taper, D-shaped optical fiber, an optical fiber with a saddle-shaped concavity in the cladding layer, and/or other functionally equivalent configurations. These are discussed in detail in patent applications A1 through A6 cited herein.

The WGM optical resonator structure may comprise a glass micro-sphere or micro-disk, a fiber-ring resonator, a semi-conductor ring/waveguide, or other functionally equivalent structure, described in detail in earlier-cited applications A1 through A6. A high-Q WGM optical resonator supports relatively narrow-linewidth resonant whispering-gallery optical modes (i.e., having a linewidth consistent with typical linewidths of a WDM system, TDM system, or other optical data transmission system), which in an optical power control device may optically couple to propagating optical modes of the fiber-optic waveguide of substantially resonant optical wavelength. The WGM optical resonator therefore provides the wavelength selectivity of the optical power control device. Once coupled into the WGM optical resonator, dissipation of the optical signal may be modulated to in turn modulate the level of transmission of the

propagating optical mode though the fiber-optic waveguide (and hence through the optical power control device), as described in the earlier-cited patent applications A1 through A6. By controllably adjusting the loss per round trip experienced by the whispering-gallery optical mode circulating within the WGM optical resonator, the optical power control device may function in either of two modes:

1) Switching the WGM optical resonator between an over-coupled condition (where the loss per round trip in the WGM optical resonator is small compared to the optical coupling between the fiber-optic waveguide and WGM optical resonator, and the transmission through the fiber-optic waveguide past the resonator is large) and the condition of critical coupling (at which the optical coupling of the fiber-optic waveguide and WGM optical resonator is substantially equal to the round trip loss of the WGM optical resonator, and substantially all of the optical power is dissipated by/from the WGM optical resonator resulting in near zero optical transmission through the fiber-optic waveguide past the WGM optical resonator); or

2) Switching states between the condition of critical coupling (near zero transmission through the fiber-optic waveguide) and a condition of under-coupling (where the loss per round trip in the WGM optical resonator is large compared to the optical coupling between the fiber-optic waveguide and WGM optical resonator, and the transmission through the fiber-optic waveguide past the WGM optical resonator is non-zero).

For all of these modes of operation, there are essentially two classes of mechanism by which one can introduce round trip loss to a circulating optical wave (i.e., resonant whispering-gallery optical mode) in the WGM resonator. Either optical power of the circulating wave can be absorbed, or it can be gated out of the WGM optical resonator into a second optical element, such as a second waveguide or second resonator. The gating may preferably be achieved by control of the optical coupling between the WGM optical resonator and the second optical element and functions rather like a trapdoor. These two general possibilities are both disclosed in earlier-cited applications A1, A2, A5, and A6. The current disclosure describes such devices in greater detail, particularly optical loss transducers or elements provided as a separate element to control optical loss from a WGM resonator by either of these means (as distinguished from designs in which the loss control element is an integral part of the WGM optical resonator structure).

SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of optical power control devices and fabrication and use thereof, and in addition may meet one or more of the following objects:

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein a modulator optical element evanescently optically coupled to a WGM optical resonator provides a controlled level of WGM resonator round-trip optical loss, enabling controlled modulation of a level of transmission of a propagating optical mode through a transmission fiber-optic waveguide (evanescently optically coupled to the WGM optical resonator) when the propagating optical mode is substantially resonant with the whispering-gallery optical mode;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises an open optical waveguide (i.e., a modulator optical waveguide);

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises a closed optical waveguide (i.e., a modulator optical resonator);

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be controlled by controlling optical absorption of the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be controlled by controlling optical power transfer from the optical resonator to the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be

controlled by controlling a resonant optical frequency of the modulator optical resonator;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises an electro-absorptive material, and application of a control electric field thereto controls the optical absorption of the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises a multi-layer distributed Bragg reflector (DBR) stack and an electro-absorptive material, and application of a control electric field thereto controls the optical absorption of the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises an electro-refractive or electro-optic material, and application of a control electric field thereto controls the optical power transfer from the WGM resonator to the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises a multi-layer distributed Bragg reflector (DBR) stack and an electro-refractive or electro-optic material, and application of a control electric field thereto controls the optical power transfer from the WGM resonator to the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical resonator comprises an electro-refractive or electro-optic material, and application of a control electric field thereto controls the resonance optical frequency of the modulator optical resonator;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the transmission fiber-optic waveguide, the WGM optical

resonator, and the modulator optical element, may be reproducibly, reliably, and stably positioned and secured within the device;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the transmission fiber-optic waveguide, the WGM optical resonator, and the modulator optical element are positioned by and secured to an alignment device; and

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the alignment device comprises first and second alignment substrates, the transmission fiber-optic waveguide is positioned and secured within an alignment groove on the first alignment substrate, the modulator optical element is secured to the second alignment substrate, the WGM resonator may be positioned and secured on the first or the second substrate, and the assembled alignment device suitably positions the modulator optical element, WGM resonator, and transmission fiber-optic waveguide relative to each other.

One or more of the foregoing objects may be achieved in the present invention by an optical power control device comprising: a) a transmission fiber-optic waveguide; b) a WGM optical resonator; c) a modulator optical element; and d) a modulator control element. The transmission fiber-optic waveguide supports a propagating optical mode (wherein flows the optical power to be controlled by the device) and is provided with an evanescent optical coupling segment where an evanescent portion of the propagating optical mode extends beyond a surface of the transmission fiber-optic waveguide. The whispering-gallery-mode (WGM) optical resonator is positioned relative to the transmission fiber-optic waveguide so that a portion of a whispering-gallery optical mode supported by the resonator at least partially spatially overlaps the evanescent portion of the propagating optical mode. The transmission fiber-optic waveguide and WGM optical resonator are thereby evanescently optically coupled. The modulator optical element is positioned so that an evanescent portion of the WG optical mode at least partially spatially overlaps the modulator optical element, thereby evanescently optically coupling the WGM optical resonator and the modulator optical element. The modulator control element is operatively coupled to the modulator optical element for modulating, in response to an applied control signal, i) a level of optical power transfer through evanescent optical coupling of the

whispering-gallery-mode optical resonator and the modulator optical element, ii) a level of optical loss (absorption or scattering) of the modulator optical element, and/or iii) a resonant frequency of the modulator optical element, thereby enabling controlled modulation of the round-trip optical loss of the WGM resonator, in turn enabling controlled modulation of a level of transmission of the propagating optical mode through the transmission fiber-optic waveguide when the propagating optical mode is substantially resonant with the whispering-gallery optical mode.

The modulator optical element may comprise an open optical waveguide or a closed optical waveguide (i.e., a modulator optical resonator). The modulator optical element may comprise an electro-absorptive material, so that application of a control electric field thereto control the optical absorption of the modulator optical element. The modulator optical element may comprise an electro-refractive or electro-optic material, so that application of a control electric field thereto controls optical power transfer from the WGM resonator into the modulator optical element. The modulator optical element may comprise a distributed Bragg reflector (DBR) stack and an electro-refractive or electro-optic material, so that application of a control electric field thereto controls optical power transfer from the WGM resonator into the modulator optical element. A modulator optical resonator may comprise an electro-refractive or electro-optic material (and may include a DBR stack), so that application of a control electric field thereto controls resonance optical frequency of the modulator optical resonator.

The transmission optical waveguide, the WGM optical resonator, and the modulator optical element may be reproducibly, reliably, and stably positioned and secured within the optical power control device using an alignment device. The alignment device comprises first and second alignment substrates, the transmission fiber-optic waveguide is positioned and secured within an alignment groove on the first alignment substrate, the modulator optical element is secured to the second alignment substrate, the WGM resonator may be positioned and secured on the first or the second substrate, and the assembled alignment device suitably positions the modulator optical element, WGM resonator, and transmission fiber-optic waveguide relative to each other.

Additional objects and advantages of the present invention may become apparent upon referring to the preferred and alternative embodiments of the present invention as illustrated in the drawings and described in the following written description and/or claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows an optical power control device according to the present invention.

Figs. 2A and 2B show side and partial sectional views, respectively, of an optical power control device according to the present invention.

Figs. 3A and 3B show partial sectional views of an optical power control device according to the present invention.

Figs. 4A and 4B show side and end views, respectively, of an optical power control device according to the present invention.

Figs. 5A, 5B, 5C, 5D, and 5E are schematic diagrams of optical power control devices according to the present invention.

Figs. 6A, 6B, and 6C show end, side, and cross-sectional views, respectively, of an optical power control device according to the present invention.

Fig. 7 shows a side view of an optical power control device according to the present invention.

Figs. 8A and 8B show side and top views, respectively, of an optical power control device according to the present invention.

Fig. 9 is a flow diagram for fabricating a modulator optical element according to the present invention.

Fig. 10 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 11 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 12 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 13 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 14 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 15 is a flow diagram for fabricating a modulator optical element according to the present invention.

Fig. 16 is a process diagram for fabricating a modulator optical element according to the present invention.

Figs. 17A, 17B, and 17C are two partial sectional views and one top view, respectively, of an optical power control device according to the present invention.

Figs. 18A, 18B, and 18C are two partial sectional views and one top view, respectively, of an optical power control device according to the present invention.

Figs. 19A and 19B are partial sectional views of an optical power control device according to the present invention.

Figs. 20A and 20B are partial sectional views of an optical power control device according to the present invention.

Figs. 21A and 21B are partial sectional views of an optical power control device according to the present invention.

Figs. 22A and 22B are partial sectional views of an optical power control device according to the present invention.

Figs. 23A and 23B are partial sectional views of an optical power control device according to the present invention.

It should be noted that the relative proportions of various structures shown in the Figures may be distorted to more clearly illustrate the present invention. In particular, the size differential and resonator thickness of fiber-rings may be greatly exaggerated relative to the underlying optical fiber diameter in various Figures for clarity. Various metal, semiconductor, and/or other thin films, layers, and/or coatings may also be shown having disproportionate and/or exaggerated thicknesses for clarity. Relative dimensions of various waveguides, resonators, optical fibers/tapers, and so forth may also be distorted, both relative to each other as well as

transverse/longitudinal proportions. For example, several Figures showing a lateral view of a fiber-taper show the length of fiber over which the taper occurs much shorter than is actually the case. The text and incorporated references should be relied on for the appropriate dimensions of structures shown herein.

It should be noted that most of the Figures may each may depict one of several distinct embodiments of an optical power control device according to the present invention. Each set of embodiments corresponding to a particular Figure are similar in spatial arrangement, but differ in functional details that are not represented in the Figures. In particular, loss-modulated, index-modulated, resonance-modulated, interference-modulated embodiments may appear substantially similar in the Figures. The particular functional aspects of the different embodiments are described in different text sections that each refer to one or more common Figures.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

For purposes of the present written description and/or claims, "whispering-gallery-mode optical resonator" (equivalently, WGM optical resonator, WGM resonator, WGMOR, WGMR) shall denote a resonator structure capable of supporting a substantially resonant whispering-gallery optical mode, the whispering-gallery optical mode typically having an evanescent portion extending beyond the whispering-gallery-mode optical resonator. Such resonator structures may include, but are not limited to, spheres, near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A7), ring or other closed waveguides, and/or functional equivalents thereof. In particular, the various WGM optical resonator structures as disclosed in earlier-cited application A5 (denoted collectively as "fiber-rings") are particularly noted for inclusion as WGM resonators for purposes of this disclosure. However, other resonator structures may be equivalently employed without departing from inventive concepts disclose and/or claimed herein. Any resonator having an evanescent portion of a resonant optical mode or that may otherwise be "evanescently optically coupled" to another optical element (see definition hereinbelow) may be employed as the resonant optical resonator element of the present invention (i.e., the element that confers wavelength specificity on the optical power control device). Optical resonator structures disclosed in earlier-cited application A7 (denoted collectively as "DBR rings") are particularly noted for inclusion as optical resonators suitable for use in the present invention. Although the term "WGM optical resonator" is used throughout the remainder of the present disclosure, it should be understood that any optical resonator that may be evanescently optically coupled to a transmission waveguide and to a modulator optical element as disclosed herein shall be considered functionally equivalent to a WGM optical resonator.

For purposes of the present written description and/or claims, "transmission fiber-optic waveguide" (equivalently, transmission waveguide, transmission fiber-optic, transmission optical fiber, TFOWG, TWG) shall denote an optical fiber (polarization-maintaining or otherwise) provided with a evanescent optical coupling segment where an evanescent portion of a

propagating optical mode may extend beyond the fiber-optic waveguide and overlap a portion of some other optical mode, thereby enabling evanescent optical coupling between the transmission optical waveguide and another optical element. Such a transmission optical waveguide may comprise an optical fiber taper, a D-shaped optical fiber, an optical fiber with a saddle-shaped concavity in the cladding layer, an optical fiber with a side-polished flattened portion, and/or functional equivalents. Such transmission optical waveguides are described in further detail in earlier-cited applications A1 through A6. Such transmission fiber-optic waveguides typically serve to facilitate insertion of optical power control devices according to the present invention into an optical power transmission system.

For purposes of the written description and/or claims, "evanescent optical coupling" shall generally denote those situations in which two optical elements, each capable of supporting a propagating and/or resonant optical mode and at least one having an evanescent portion extending beyond its respective optical element, are optically coupled by at least partial spatial overlap of the evanescent portion of one optical mode with at least a portion of the other optical mode. The amount, strength, level, or degree of optical power transfer from one optical element to the other through such evanescent optical coupling depends on the spatial extent of the overlap (both transverse and longitudinal), the spectral properties of the respective optical modes, and the relative spatial phase matching of the respective optical modes (also referred to as modal index matching). To transfer optical power most efficiently, the respective modal indices of the optical modes (equivalently, the respective modal propagation constants), each in its respective optical element, must be substantially equal. Mismatch between these modal indices decreases the amount of optical power transferred by evanescent coupling between the optical elements, since the coupled modes get further out of phase with each other as each propagates within its respective optical element and the direction of the optical power transfer eventually reverses itself. The propagation distance over which the modes interact (i.e., the effective interaction length) and the degree of index matching (or mis-matching) together influence the overall flow of optical power between the coupled modes. Optical power transfer between the coupled modes oscillates with a characteristic amplitude and spatial period as the modes propagate, each in its respective optical element. Neglecting the effects of optical loss in the optical elements, the optical power transfer amplitude is determined primarily by the phase mismatch (substantially

complete optical power transfer with little phase mismatch; decreasing optical power transfer with increasing phase mismatch). The optical power transfer spatial period is determined by the degrees of transverse spatial overlap and phase mismatch (shorter spatial period for greater overlap; shorter spatial period for larger phase mismatch). By controlling the phase mismatch and/or transverse spatial overlap, these characteristics may be exploited for controlling optical power transfer between optical elements. For example, by altering the phase mismatch, a device may be switched from a first condition, in which a certain fraction of optical power is transferred from a first optical mode in a first optical element to a second optical mode in a second optical element (phase mismatch set so that the effective interaction length is about half of the characteristic spatial period described above), to a second condition in which little or no optical power is transferred (phase mismatch set so that the effective interaction length is about equal to the characteristic spatial period). Further discussion of optical coupling may be found in Fundamentals of Photonics by B. E. A. Saleh and M. C. Teich (Wiley, New York, 1991), hereby incorporated by reference in its entirety as if fully set forth herein. Particular attention is called to Chapters 7 and 18.

It should be noted that optical power control devices, their fabrication, and their use according to the present invention are intended primarily for modulating a propagating optical mode having a wavelength between about 0.8 μm and about 1.7 μm (the wavelength range typically utilized for fiber-optic telecommunications). However, these devices, methods of fabrication, and methods of use may be adapted for use at any desired wavelength while remaining within the scope of inventive concepts disclosed and/or claimed herein.

A typical optical power control device according to the present invention is shown schematically in Fig. 1. In subsequent Figures, specific embodiments for transmission optical waveguide 110, whispering-gallery-mode resonator 120, and/or alignment structures therefor may be shown. These are illustrative and exemplary, and should not be construed as limiting the scope of the present invention as shown, described, and/or claimed except when specifically recited in a particular claim. Transmission waveguide 110 is typically an optical fiber taper, although a side etched optical fiber (as in earlier-cited application A6) is also shown, and any other transmission waveguide having a suitable evanescent coupling segment may be equivalently employed. WGM resonator 120 is typically shown as fiber-ring resonator (as in

earlier-cited application A5), although any other optical resonator suitable for evanescent optical coupling to a transmission waveguide and a modulator optical element may be equivalently employed. A propagating optical mode enters an input end 112 of transmission fiber-optic waveguide 110, and exits an output end 114 of transmission waveguide 110. Transmission waveguide 110 is provided with an evanescent optical coupling segment 116 where an evanescent portion of the propagating optical mode may extend beyond the transmission waveguide 110. Evanescent optical coupling segment 116 may comprise a tapered segment of a fiber taper transmission optical waveguide (as described, for example, in earlier-cited applications A1 through A5), a saddle- or pit-shaped evanescent coupling portion of a cladding layer surface of a fiber-optic waveguide (as described in earlier-cited application A6), or other functionally equivalent structure. A whispering-gallery-mode optical resonator 120 supports a substantially resonant whispering-gallery optical mode, having an evanescent portion extending beyond the whispering-gallery-mode optical resonator. The WGM optical resonator 120 is positioned relative to the evanescent coupling segment of the transmission waveguide 110 so that the evanescent portion of the propagating optical mode at least partially spatially overlaps a portion of the whispering-gallery optical mode, thereby evanescently optically coupling the WGM resonator 120 and the transmission waveguide 110. The WGM optical resonator 120 provides the wavelength selectivity of control device. Unless the propagating optical mode is substantially resonant with a whispering-gallery resonant optical mode of the WGM resonator 120, optical coupling of the propagating optical mode into and/or circulation of its radiation within the WGM resonator 120 is/are negligible, and the propagating optical mode is transmitted through the transmission waveguide 110 substantially unaffected by the presence of WGM resonator 120 or the operational state of control device. (Hence the phrase "resonant optical power control device".)

In contrast, when the propagating optical mode is substantially resonant with a whispering-gallery resonant optical mode of WGM resonator 120, optical coupling of the propagating optical mode into and circulation of its radiation within WGM optical resonator 120 may be quite substantial. For a relatively high-Q WGM optical resonator (on the order of 10^6 may be achieved; 10^4-10^5 typically employed in devices according to the present invention), the level of circulating optical power in the whispering-gallery optical mode may reach a level many

times higher than the power level of the propagating optical mode. Slight changes in the optical loss per round trip for this circulating radiation dramatically affects the level of transmission of the propagating optical mode through the transmission waveguide 110. By controllably adjusting this optical loss per round trip, resonant optical power control device may function in either of two modes:

1) Switching the optical loss between i) an over-coupled condition (where the optical loss per round trip in the WGM optical resonator 120 is small compared to the optical coupling between the transmission waveguide 110 and WGM optical resonator 120) in which the transmission of the propagating optical mode through transmission waveguide 110 past the WGM resonator is large, and ii) a condition of critical coupling (where the optical loss per round trip in the WGM optical resonator 120 is substantially equal to optical coupling of transmission waveguide 110 and WGM optical resonator 120) in which substantially all of the optical power is dissipated by/from the WGM optical resonator resulting in near zero optical transmission of the propagating optical mode through transmission waveguide 110 past WGM optical resonator 120; or

2) Switching the optical loss between i) the condition of critical coupling with near zero transmission through transmission waveguide 110, as described above, and ii) a condition of under-coupling (where the optical loss per round trip in the WGM optical resonator 120 is large compared to the optical coupling between the transmission waveguide 110 and WGM optical resonator 120) in which the transmission of the propagating optical mode through transmission waveguide 110 past WGM optical resonator 120 is non-zero.

For purposes of the present written description and/or claims, it shall be assumed (unless specifically stated otherwise) that the propagating optical mode (whose optical power transmission through the transmission fiber-optic waveguide is to be controlled by device) is substantially resonant with the whispering-gallery resonant optical mode (supported by the WGM optical resonator).

A modulator optical element 130 is positioned relative to WGM optical resonator 120 so that an evanescent portion of the whispering-gallery optical mode at least partially spatially overlaps at least a portion of an optical mode of modulator optical element 130. Modulator

optical element 130 is thereby evanescently optically coupled to WGM optical resonator 120. Modulator optical element 130 serves to enable controlled adjustment of the round trip optical loss of WGM optical resonator 120 between over-, critical-, and/or under-coupled conditions in one of several of ways: i) modulator optical element 130 may provide a controlled level of direct optical loss of the whispering-gallery optical mode (collectively referred to herein as "loss-modulated" or more specifically "absorption-modulated" devices); ii) a level of evanescent optical coupling between WGM optical resonator 120 and modulator optical element 130 may be controlled, with radiation coupled from WGM resonator 120 into modulator optical element 130 absorbed within, transmitted away from, and/or otherwise dissipated from the modulator optical element 130 (collectively referred to herein as "coupling-modulated" or more specifically "index-modulated" devices); iii) a resonant frequency of a resonant modulator optical element 130 may be controlled, so that modulator optical element only provides loss for the whispering-gallery optical mode when one of the modulator resonance frequencies substantially coincides with the whispering-gallery mode frequency (collectively referred to herein as "resonance-modulated" devices); and iv) a modulator optical element 130 may be evanescently optically coupled to the WGM resonator 120 at two separate points and the modulator modal index may be controlled, enabling interferometric control of the round-trip loss of WGM resonator 120 (collectively referred to herein as "interference-modulated" devices). Modulator control element(s) 170 is/are operatively coupled to the modulator optical element 130 for enabling control of the round trip loss of the WGM resonator 120 by application of a control signal, in turn enabling controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

In a first group of embodiments of the present invention, a level of direct optical loss of the whispering-gallery optical mode by the modulator optical element is controlled to enable controlled modulation of transmission of the propagating optical mode through the transmission waveguide. The modulator optical element in these so-called "loss-modulated" or "absorption-modulated" embodiments may comprise an open optical waveguide structure (in which an optical mode of the waveguide does not follow a closed path and re-circulate and/or resonate within the waveguide; referred to hereinafter as a "modulator waveguide"), or may comprise an ring, resonator (including a second whispering-gallery-mode optical resonator), or other closed

optical waveguide structure (in which an optical mode of the waveguide may re-circulate and/or resonate; referred to collectively hereinafter as a "modulator resonator"). In either case, the modulator optical element is positioned so that an evanescent portion of the whispering-gallery optical mode at least partially spatially overlaps an optical mode of the modulator optical element. A modulator optical element incorporating material whose optical absorption, at the wavelength of the whispering-gallery optical mode, can be controlled thereby enables control of the round trip optical loss experienced by the whispering-gallery optical mode in the WGM resonator, in turn achieving the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide as described above.

Absorption-modulated embodiments of an optical power control device according to the present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical element comprises an open modulator optical waveguide positioned tangentially with respect to the WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic waveguide having an evanescent coupling portion of the cladding layer surface as described in detail in earlier-cited application A6, or other fiber-optic waveguide having an evanescent coupling portion could be equivalently employed. WGM optical resonator 120 is shown in Figs. 2A, 2B, 3A, and 3B as a fiber-ring resonator as described in detail in earlier-cited application A5. Other WGM resonator structures could be equivalently employed, including but not limited to a rings, spheres or near-spheres, disks, microspheres, microdisks, or other resonator geometry as recited hereinabove. In Figs. 2A and 2B, the modulator optical element is a slab waveguide 132 in substantial tangential engagement with WGM resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator to yield a desired level of evanescent optical coupling.

An evanescent portion of the whispering-gallery optical mode supported by WGM resonator 120 extends radially beyond the circumference thereof, and therefore spatially overlaps a portion of an optical mode of the slab waveguide 132. Absorption-modulated slab waveguide 132 may preferably be fabricated incorporating a material having an optical loss (typically optical absorption), at the wavelength of the whispering-gallery optical mode, which may be controlled by a modulator control element. The optical absorption per unit length in the interaction region is preferably sufficiently large to enable the WGM resonator round trip optical

the slab and WGM resonator might be well phase-matched and the optical loss of the slab chosen to produce a critical-coupling condition at the fiber-optic waveguide/resonator junction, while the optical absorption of the slab may be switched to a higher level to yield an under-coupled condition at the fiber-optic waveguide/resonator junction. Many other schemes and combinations of phase match/mismatch and operative levels of optical absorption of the slab waveguide may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. For a given WGM optical resonator geometry, slab waveguide material, and so forth, some experimentation is typically required to determine the level of evanescent coupling, and the appropriate levels of slab waveguide optical loss to produce the desired modulation of the WGM resonator round trip loss.

In Figs. 3A and 3B, the modulator optical element is an absorption-modulated two-dimensional (2D) waveguide 134 on a substrate 136 and positioned tangentially with respect to WGM optical resonator 120. Many of the same considerations applicable to the absorption-modulated slab waveguide embodiment of Figs. 2A and 2B apply to the absorption-controlled 2D waveguide embodiment of Figs. 3Aand 3B. The 2D waveguide 134 may preferably be fabricated incorporating a material having an optical absorption at the wavelength of the whispering-gallery optical mode that may be controlled by a modulator control element, and which may produce WGM resonator round trip loss sufficient to achieve critical coupling. Modal index mismatch between the 2D waveguide and the WGM optical resonator must be controlled in the manner described hereinabove for the absorption-controlled slab waveguide. In addition to the 2D waveguide material and the substrate material, the transverse geometry of the 2D waveguide must also be chosen to yield the desired spatial overlap and phase match/mismatch properties.

The optical absorption of absorption-modulated slab waveguide 132 or 2D waveguide 134 may be controlled by electronic, optical, and/or other means. For example, a quantum well, multi-quantum well (MQW), other semi-conductor, or other functionally equivalent material may be incorporated into the modulator waveguide as an electro-absorptive material, wherein the optical absorption of the modulator waveguide may be altered by application of a co[illegible] field. A modulator control element may comprise control electrodes suitably positio[illegible] the control electric field. Alternatively, the optical absorption by such materials may

controlled by injection of current into the material. The presence of additional charge carriers (electrons and/or holes, as the case may be) may serve to increase or decrease the optical absorption of the waveguide material, depending on the bandgap, band structure, and/or doping of the electro-absorptive material and the wavelength of the optical mode to be modulated. Control electrodes or other electrical contacts may serve to inject a control electrical current. Optical excitation of such materials may also serve to generate charge carriers, thereby enabling control of the waveguide optical absorption by application of an optical control signal. Other classes of materials exhibiting photo-bleaching, excited state absorption, saturable absorption, and/or non-linear optical absorption may be equivalently incorporated into the modulator waveguide to enable control of the waveguide optical absorption by application of an optical control signal.

A preferred material for fabricating slab waveguide 132 and/or 2D waveguide 134 comprises a multi-quantum well (MQW) material comprising alternating layers of i) quantum well layers of a material having a bulk bandgap close to or only slightly larger (within about 10 meV to 30 meV, for example) than the photon energy of the whispering-gallery optical mode, and ii) barrier layers having a bandgap substantially larger than the photon energy of the propagating optical mode. The bandgaps referred to here are not the bulk bandgaps for the various materials, but the bandgaps of the materials as incorporated as individual layers of a multi-layer structures described. The MQW material is surrounded by a pair of contact layers (doped or otherwise) for facilitating electrical contact to the control electrodes. Delta-doping of the contact layers may be preferred, to minimize unwanted diffusion of dopant(s) into the MQW material. The control signal comprises a control voltage applied across the electrodes, thereby applying a control electric field substantially normal to the layers of the MQW material. This electric field may red-shift resonance(s) of the MQW material with respect to the frequency of the whispering-gallery optical mode through a quantum-confined Stark effect (QCSE), a Franz-Keldysh effect (FKE), a quantum-confined Franz-Keldysh effect (QCFKE), or other similar mechanism. Typically, the electro-absorptive MQW material would be chosen having a resonance i) slightly above the photon energy of the whispering-gallery optical mode in the absence of a control electric field, and ii) slightly below the photon energy of the whispering-gallery optical mode when red-shifted by application of the control electric field. In this way

application of the control signal alters the optical loss experienced by the whispering-gallery optical mode, in turn altering the transmission level of the propagating optical mode through the transmission waveguide.

In an exemplary embodiment for controlling wavelengths typically used for long-haul fiber-optic telecommunications (between about 1.2 μm and about 1.7 μm), the quantum well layers, barrier layers, and doped contact layers may comprise InGaAsP, the quantum well layers may be between about 7 nm thick and about 15 nm thick with a bulk bandgap between about 1.3 μm and about 1.6 μm, the barrier layers may be between about 20 μm thick and about 50 nm thick with a bulk bandgap between about 1.0 μm and about 1.4 μm, and the doped contact layers may be between about 20 nm thick and about 100 nm thick. In a preferred embodiment, the quantum well layers may be about 10 nm thick with a bulk bandgap of about 1.6 μm, the barrier layers may be about 20 nm thick with a bandgap of about 1.2 μm, and the delta-doped contact layers may be about 50 nm thick. Many such MQW materials are readily available commercially, and may be specified by layer thickness, layer bandgap, and layer composition. The bulk bandgap of a particular layer material may be generally well-known and determined by the precise composition/stoichiometry of the material, while the layer bandgap may often be determined in a well-known manner from a combination of layer composition/stoichiometry, layer thickness, and/or structural strain induced by adjacent layers. Many material combinations (extant or hereafter developed), layer thicknesses, and bandgaps may be employed for modulating many other optical wavelengths without departing from inventive concepts disclosed and/or claimed herein. Several alternative material combinations are disclosed in earlier-cited application A7.

An absorption-modulated embodiment of an optical power control device according to the present invention is shown in Figs. 4A and 4B in which the modulator optical element comprises an open arcuate modulator optical waveguide 138 positioned axially with respect to the WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-cited application A5. Other optical resonator structures could be equivalently employed. In Fig.

4A spacer 139 is shown for positioning arcuate waveguide 138 at the proper distance from WGM resonator 120. In this particular embodiment the spacer 139 comprises a portion of an adjacent fiber segment connected to the fiber-ring resonator with arcuate waveguide 138 deposited thereon, bonded thereto, or otherwise held in contact therewith. Some experimentation will typically be required to determine the spacing between WGM resonator 120 and arcuate waveguide 138 that produces the desired level of round-trip optical loss for WGM resonator 120 and the appropriate phase matching conditions between WGM resonator 120 and arcuate waveguide 138. Once the proper thickness of spacer 139 has been determined, it may be reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, or other suitable processing of the adjacent fiber segment. A functionally equivalent spacer may be employed for other types of optical resonator as well. The same types of materials used for the absorption-modulated slab and 2D waveguides described hereinabove may be employed for fabricating absorption-modulated arcuate waveguide 138. In particular, arcuate waveguide 138 may comprise the InGaAsP multi-quantum well material described hereinabove, with the alternating quantum well and barrier layers and surrounding contact layers substantially parallel to WGM resonator 120 and with the control electric field applied substantially perpendicular to WGM resonator 120. An advantage of this embodiment is increased interaction length between the whispering-gallery optical mode and the arcuate waveguide relative to the tangentially positioned waveguides of Figs. 2A, 2B, 3A, and 3B, therefore requiring smaller optical loss per unit distance to achieve the same round trip optical loss in the WGM resonator.

A significant property of both tangentially- and axially-positioned absorption-modulated open modulator optical waveguide structures is that since no re-circulation of any waveguide optical mode occurs, the presence of the modulator optical waveguide has a substantially negligible effect on the wavelength-dependent properties and/or resonant behavior of the adjacent WGM optical resonator. Such wavelength/frequency shifting behavior can adversely affect the performance of an optical power control device according to the present invention, or alternatively may be exploited to enhance said performance, depending on the design, construction, and use of a particular device.

Various absorption-modulated embodiments of an optical power control device according to the present invention are shown schematically in Figs. 5A through 5E in which the modulator

optical element comprises a closed optical waveguide (i.e., a modulator optical resonator 140) positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with respect to the WGM resonator 120, and oriented substantially parallel to (Figs. 5A, 5C, and 5D) or substantially perpendicular to (Figs. 5B and 5E) the WGM resonator 120. Transmission waveguide 110 is shown (in cross-section) as a tapered fiber-optic waveguide. A fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM optical resonator is shown generically as a micro-disk or micro-ring resonator. Other optical resonator structures, such as the fiber-rings of earlier-cited application A5, could be equivalently employed. Absorption-modulated modulator optical resonator 140 may comprise any of the resonator structures recited earlier for WGM resonator 120, including but not limited to spheres, near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A7), ring or other closed waveguides, and/or functional equivalents thereof, and are shown generically as micro-disks or micro-rings in Figs. 5A through 5E. Absorption-modulated modulator optical resonator 140 is shown in Figs. 5A and 5B in substantial tangential engagement with WGM optical resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical mode extending radially beyond WGM resonator 120 may overlap a portion of an optical mode of modulator optical resonator 140, either a radially-extending portion thereof when substantially parallel to WGM resonator 120 (Fig. 5A), or an axially-extending portion thereof when substantially perpendicular to WGM resonator 120 (Fig. 5B). Absorption-modulated modulator optical resonator 140 is shown in Figs. 5C, 5D, and 5E positioned axially with respect to WGM optical resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical mode extending axially beyond WGM resonator 120 may overlap a portion of modulator optical resonator 140, either an axially-extending portion thereof when substantially parallel to WGM

resonator 120 (Figs. 5C and 5D), or a radially-extending portion thereof when substantially perpendicular to WGM resonator 120 (Fig. 5E).

Absorption-modulated modulator optical resonator 140 may preferably be fabricated incorporating material having an optical loss (typically optical absorption), at the wavelength of the whispering-gallery optical mode, that may be controlled by a modulator control element. The modulator optical resonator 140 should preferably have a resonant optical mode having substantially the same wavelength as the whispering-gallery optical mode of WGM resonator 120 (and hence the propagating optical mode to be controlled). This enables transfer of optical power from the WGM resonator and build-up of optical power within the modulator optical resonator, in turn enabling a relatively small optical loss per unit length in the modulator optical resonator to produce sufficiently large round trip optical loss for the WGM resonator coupled thereto. If the modulator optical resonator and WGM optical resonator are not resonant with each other, in contrast, the situation becomes analogous to that described hereinabove for the open modulator waveguide embodiments, with relatively large optical loss per unit length required in the modulator optical resonator to generate sufficient round trip optical loss for the WGM resonator. A complication encountered when implementing an embodiment that includes an absorption-modulated modulator resonator arises from the unavoidable wavelength shift of the resonant optical mode of the modulator resonator that occurs with a change in the optical loss thereof. The WGM resonator and modulator optical resonator must be treated as a coupled-cavity system, and shifts in the modulator resonance wavelength may perturb the resonances of the coupled system. This effect must be properly accounted for in designing an optical power control device incorporating a modulator optical resonator, or alternatively, the effect may be exploited for designing optical power control devices with specific wavelength dependent performance characteristics. This effect may be somewhat mitigated for an absorption-modulated resonator modulator element, since the optical loss of such a modulator resonator tends to reduce the finesse of the modulator resonator and increase the bandwidth of its resonances, in turn decreasing the effect of the modulator resonances on the WGM resonances in the coupled-cavity system. In short, loss- or absorption-modulated resonator or "closed waveguide" modulator optical elements having relatively low finesse (less than about 10) may behave substantially less "resonator-like" than the relatively high-finesse WGM resonator.

The optical absorption of modulator optical resonator 140 may be controlled by electronic, optical, and/or other means in ways completely analogous to those recited for the modulator waveguides hereinabove, and utilizing the same and/or functionally equivalent materials for fabrication and the same and/or functionally equivalent modulator control elements. For example, a quantum well, multi-quantum well (MQW), or other semi-conductor material may be incorporated into the modulator optical resonator as an electro-absorptive material, wherein the optical absorption may be altered by application of a control electric field. A modulator control element may comprise control electrodes suitably positioned to apply the control electric field. Materials described hereinabove (for modulator waveguides), such as an InGaAsP MQW material controlled by a QCSE, FKE, QCFKE, or similar mechanism, are also suitable for incorporation into modulator resonator 140. The optical absorption by such quantum well, MQW, and other semi-conductor materials may alternatively be controlled by injection of current into the material. The presence of additional charge carriers (electrons and/or holes, as the case may be) may serve to increase or decrease the optical absorption of the waveguide material, depending on the bandgap, band structure, and/or doping of the semiconductor and the wavelength of the optical mode to be modulated. Control electrodes or other electrical contact may serve to inject a control electrical current. Optical excitation of such materials may also serve to generate carriers, thereby allowing control of the waveguide optical absorption to be controlled by application of an optical control signal. Other classes of materials exhibiting photo-bleaching, excited state absorption, saturable absorption, and/or non-linear optical absorption may be equivalently incorporated into the modulator resonator to enable control of the waveguide optical absorption by application of an optical control signal.

The interaction region (i.e., the volume of overlap between the evanescent portion of the whispering-gallery optical mode and the modulator optical resonator) is typically limited in spatial extent by the geometries of the embodiments of Figs. 5A, 5B, 5D, and 5E, limiting the distance over which phase matching must be controlled. Significantly more stringent phase matching constraints may arise for the embodiment of Fig. 5C, in which WGM resonator 120 and modulator resonator 140 are substantially coaxial, since the interaction region extends entirely around the WGM resonator 120. The entire modulator 140 need not have controlled optical loss. It may be desirable to leave the interaction region without absorption-controlled

material, so that altering the absorption of the modulator resonator does not affect the phase matching condition in the interaction region.

For the embodiments of Figs. 5A through 5E, the relative positioning of WGM resonator 120 and modulator resonator 140 must be reliable, reproducible, and stable. For a given combination of WGM resonator (material(s) and/or geometry) and modulator (material(s) and/or geometry), some experimentation will be necessary to determine the relative position resulting in the desired degree of evanescent optical coupling therebetween (based on the degree of spatial overlap and relative phase matching). Once the proper relative positioning has been determined, a mechanical spacer or other suitable alignment aid may be employed to enable reliable, reproducible, and stable relative positioning of the WGM resonator and the modulator optical resonator in an optical power control device according to the present invention. Such spacers may comprise a member integrally formed with the WGM resonator, a member integrally formed with the modulator optical resonator, or an independent member fabricated independently of either resonator. Economies of fabrication and/or assembly of the optical control device may be realized when the spacer is integrally formed with one or the other of these resonators.

Figs. 6A, 6B, and 6C show an optical power control device wherein: fiber-optic waveguide 110 comprises a fiber-optic taper (another type of fiber-optic waveguide, including a fiber-optic waveguide having a saddle-shaped coupling surface, could be equivalently employed); WGM optical resonator 120 comprises a fiber-ring resonator; and modulator resonator 140 comprises a ring of MQW material (as described above or otherwise) deposited on, bonded to, or otherwise held in contact with an adjacent fiber segment 141 connected to the fiber-ring. This embodiment corresponds to the arrangement shown schematically in Fig. 5C. The adjacent fiber segment 141 serves as a mechanical spacer for reliable, reproducible, and stable positioning of modulator resonator 140 relative to the fiber-ring. Once the proper thickness of the spacer (i.e., adjacent fiber segment 141) has been determined, it may be reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, and/or other suitable processing of the adjacent fiber segment. Layers 172 and 174 may comprise contact layers and/or electrodes for applying a control electric field to a modulator resonator 140 comprising an electro-absorptive material as enumerated and disclosed

hereinabove. Fig. 7 shows a similar embodiment in which the fiber-ring is fabricated from PANDA-type polarization preserving optical fiber. One or more internal structural elements 142 of the PANDA fiber, protruding axially from fiber-ring WGM resonator 120, serve as the spacer for maintaining reliable, reproducible, and stable relative positioning of the fiber-ring WGM resonator and modulator resonator 140 (a micro-disk in this example, which may include contact/electrode layers not shown). Modulator resonator 140 may be bonded to or otherwise held in contact with structural elements 142. Structural elements 142 may preferably be left protruding from the fiber-ring by differential etching of the fiber-ring and the structural elements, or may result from any suitable machining, lithographic, or other processing technique for producing such structures.

A more elaborate embodiment of an optical power control device according to the present invention is shown in Figs. 8A and 8B. Fiber-optic waveguide 110 comprises a fiber-optic taper (another type of fiber-optic waveguide, including a fiber-optic waveguide having a saddle-shaped coupling surface, could be equivalently employed). WGM optical resonator 120 comprises a fiber-ring resonator. Modulator optical element 140 is fabricated on a semi-conductor substrate and comprises a disk incorporating MQW material, and in this case may have a relatively low Q-factor (i.e., less resonator-like). Modulator element 140 nevertheless may provide a controlled level of optical loss for fiber-ring resonator around substantially the entire circumference of the fiber-ring resonator, enabling substantially full modulation of optical power transmitted through fiber taper 110 through relatively small changes in the absorption per unit length of modulator element 140. For wavelengths in the 1.2 μm to 1.7 μm range, a preferred substrate material is InP, while a preferred MQW material is an InGaAsP MQW layer 147 surrounded by delta-doped InGaAs contact layers 148 and 149, which enable application of control voltages via bottom electrode 178 (via delta-doped InGaAs layer 177 and doped InP spacer 179) and top ring electrode 176. An insulating layer 175 may also be provided. These materials have been described in detail hereinabove, and other suitable substrate and resonator materials may be equivalently employed. By depositing an appropriate sequence of epitaxial layers and suitably processing, modulator optical resonator 140 and associated control electrodes 176 and 178 may be fabricated on substrate 144, which may also include a central spacer 146. The height of spacer 146 may be controlled to nanometer precision through standard epitaxial

growth techniques, and the fiber-ring resonator may be bonded to or otherwise held in contact with spacer 146 to achieve reliable, reproducible, and stable relative positioning of modulator optical resonator 140 and WGM fiber-ring resonator 120.

In a second group of embodiments of the present invention, a level of optical power transfer from the whispering-gallery optical mode to the modulator optical element 130 (through evanescent optical coupling) is controlled by modulating the relative phase matching of the whispering-gallery optical mode and a modulator optical mode in the interaction region thereof. The modulator optical element 130 in these so-called "index-modulated" embodiments may comprise an open optical waveguide structure (in which an optical mode of the waveguide does not follow a closed path, re-circulate, or resonate within the waveguide; referred to hereinafter as a "modulator waveguide"), or may comprise a ring, resonator, or other closed optical waveguide structure (in which an optical mode of the waveguide may re-circulate and/or resonate; referred to collectively hereinafter as a "modulator resonator"). These modulator elements may be either low-finesse (less than about 10; less "resonator-like") or high-finesse (greater than about 10; more "resonator-like"), depending on the particular device configuration employed. In either case, the modulator optical element 130 is positioned so that an evanescent portion of the whispering-gallery optical mode at least partially spatially overlaps a modulator optical mode whose modal index may be controlled, thereby enabling control of optical power transfer via evanescent optical coupling (by control of phase matching) between the WGM resonator 120 and the modulator waveguide 130. This in turn controls the round trip optical loss experienced by the whispering-gallery optical mode in the WGM resonator 120, thereby enabling the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

In a third group of embodiments of the present invention, a modulator optical element 130 may comprise a modulator optical resonator for supporting a modulator optical mode whose modal index may be controlled, thereby also shifting a resonance wavelength thereof. In such "resonance-modulated" embodiments, optical power transfer (through evanescent optical coupling) from the whispering-gallery optical mode to a modulator optical mode is controlled by shifting the modulator optical mode into and/or out of resonance with the whispering-gallery optical mode. This in turn controls the round trip optical loss experienced by the whispering-

gallery optical mode in the WGM resonator 120, thereby enabling the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

In a fourth group of embodiments of the present invention, a modulator optical element 130 may comprise a modulator optical waveguide or resonator, evanescently optically coupled to the WGM optical resonator 120 at two separate points, for supporting a modulator optical mode whose modal index between the two points may be controlled. In such "interference-modulated" embodiments, net optical power transfer (through evanescent optical coupling) from the whispering-gallery optical mode to a modulator optical mode is controlled by controlling the relative phase of the modulator optical mode and the whispering-gallery optical mode at the second coupling region. This in turn controls the round trip optical loss experienced by the whispering-gallery optical mode in the WGM resonator 120, thereby enabling the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

A property common to each of the second, third, and fourth groups of embodiments is control of the modal index of a modulator optical mode in response to an applied control signal. This may be preferably achieved by use of a modulator waveguide or resonator fabricated incorporating an electro-refractive material, an electro-optic material and/or a non-linear optical material, thereby enabling control of the modal index through application of an electronic and/or optical control signal.

Examples of suitable electro-optic materials (typically non-centrosymmetric) include, but are not limited to: semiconductor materials, including zincblende semiconductors; quantum well materials; multi-quantum well (MQW) materials, including materials exhibiting the quantum confined Stark effect (QCSE), Franz-Keldysh effect (FKE), quantum-confined Franz Keldysh effect (QCFKE), or similar mechanism; crystalline oxide electro-optic materials such as lithium niobate (LNB), potassium niobate (KNB), potassium dihydrogen phosphate (KDP), and so forth; organic and/or polymeric electro-optic materials, including poled chromophore-containing polymers; liquid crystals; hybrid layered materials comprising an electro-optic layer in contact with or incorporated within a Bragg multi-layer dielectric stack for supporting surface-guided optical modes (SGOMs) such as surface-guided Bloch modes (SGBMs), for example; hybrid

layered materials comprising an electro-optic layer in contact with, incorporated within, or positioned between a pair of Bragg multi-layer dielectric stacks; combinations thereof; and/or functional equivalents thereof. A modulator control element may comprise control electrodes operatively coupled to the modulator optical element for enabling control of the modal index of the modulator optical mode in the modulator optical element by application of an electronic control voltage and/or current to the electro-optic or electro-refractive material. Optical excitation of some of these materials may also serve to generate charge carriers, thereby enabling control of the modal index by application of an optical control signal. Materials exhibiting non-linear optical polarizability, saturable optical polarizability, non-linear Kerr effect, and/or other non-linear optical responses may be incorporated into the modulator optical element to enable control of the modal index thereof by application of an optical control signal.

Index-modulated embodiments of an optical power control device according to the present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical element comprises an open modulator optical waveguide positioned tangentially with respect to the WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-cited application A5. Other WGM resonator structures could be equivalently employed. In Figs. 2A and 2B, the modulator optical element is a slab waveguide 132 in substantial tangential engagement with WGM resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator to yield a desired level of evanescent optical coupling.

An evanescent portion of the whispering-gallery optical mode supported by WGM resonator 120 extends radially beyond the circumference thereof, and therefore spatially overlaps a portion of the slab waveguide 132. Index-modulated slab waveguide 132 may preferably be fabricated incorporating an electro-optic or electro-refractive material, so that the modal index of a modulator optical mode may be controlled by a modulator control element. The electro-optic material need only be present in the interaction region (i.e., the volume of overlap between the evanescent portion of the whispering-gallery optical mode and the slab waveguide) which is

typically limited in spatial extent by the size and curvature of WGM resonator 120, although the electro-optic material may also be present elsewhere in the waveguide. The modal index shift in response to a control signal may preferably be sufficiently large to enable the WGM resonator round trip optical loss (due to evanescent coupling into the modulator waveguide) to reach a level comparable to the optical coupling between the transmission waveguide 110 and the resonator 120 (i.e., to achieve critical coupling; typically loss on the order of about 0.5% to about 5% per round trip is needed to yield linewidths consistent with typical WDM, TDM, or other optical data transmission systems; typically on the order of 1-40 GHz), or alternatively, to enable the WGM resonator round trip loss to exceed critical coupling. The slab waveguide should be kept thin (comparable to the radial extent of the evanescent portion of the whispering-gallery optical mode beyond the circumference of resonator 120) and the index of refraction of any substantially homogeneous medium in contact with the face of the slab opposite the WGM resonator (i.e., a substrate or cladding layer) must be less than the refractive index of the slab waveguide and no greater than the refractive index of the WGM resonator. In this way optical power is confined within waveguide 132 near resonator 110, thereby substantially eliminating undesired optical loss. Otherwise optical power coupled from the WGM resonator 120 into slab waveguide 132 could propagate away from resonator 110 and be lost.

Modal index mismatch (i.e., phase mismatch) between the whispering-gallery optical mode and the slab waveguide must be carefully controlled so that, by switching the slab waveguide modal index between two operational levels, the round trip optical loss of the WGM optical resonator (due to coupling of optical power into the modulator waveguide and dissipation therefrom) may be switched between under- and critically-coupled conditions, or between critically- and over-coupled conditions. For example, the slab waveguide material might be chosen to yield a relatively large phase mismatch, thereby limiting the transfer of optical power to the slab (characteristic spatial period short compared to interacting propagation distance) and resulting in over-coupling, while the application of a control signal may change the modal index so as to reduce the phase mismatch (thereby lengthening the spatial period) and thereby increase transfer of optical power to the slab to a sufficiently high level to result in critical-coupling and near-zero transmission of the propagating optical mode through the transmission optical waveguide. In a second example, the slab and WGM resonator might be well phase-matched

and the coupling chosen to yield a critical-coupling condition (interaction length about one-half the characteristic spatial period), while the modal index of the slab may be switched to a level that results in phase-mismatch (interaction length roughly equal to the characteristic spatial period) and an over-coupled condition. Many other schemes and combinations of modal index operational levels and phase match/mismatch between the WGM resonator and the slab waveguide may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. For a given WGM optical resonator geometry, slab waveguide material, and so forth, some experimentation is typically required to determine the level of evanescent coupling, and the appropriate operational levels of slab waveguide modal index to produce the desired modulation of the WGM resonator round trip loss.

Dissipation of optical power from the modulator waveguide may be achieved in a variety of ways. The optical power may be allowed to simply propagate in the modulator waveguide away from the interaction region to radiate into the environment, without an opportunity to couple back into the WGM resonator. Alternatively, the modulator waveguide may be provided with a region of high optical loss (which need not be modulated). The high-loss region may encompass all or a portion of the modulator waveguide, and may or may not be spatially separate from the interaction region. The optical loss may be provided in myriad functionally equivalent ways, including but not limited to optical absorption and optical scattering, and optical power coupled into the modulator waveguide from the WGM resonator may propagate in the region of high optical loss and be absorbed or otherwise dissipated. Any functionally equivalent means for dissipating optical power transferred into the modulator waveguide from the WGM optical resonator may be employed without departing from inventive concepts disclosed and/or claimed herein.

In Figs. 3A and 3B, the modulator optical element is an index-modulated two-dimensional (2D) waveguide 134 on a substrate 136 and positioned tangentially with respect to WGM optical resonator 120 (in this example a fiber-ring WGM resonator as described in earlier cited application A5; other WGM structures may be equivalently employed). Most of the same considerations applicable to the index-modulated slab waveguide embodiment of Figs. 2A and 2B apply to the 2D waveguide embodiment of Figs. 3Aand 3B. The 2D waveguide 134 may preferably be fabricated incorporating an electro-optic or electro-refractive material, so that the

modal index of a modulator optical mode may be controlled by a modulator control element, and which may produce WGM resonator round trip loss sufficient to achieve critical coupling. Modal index mismatch between the 2D waveguide and the WGM optical resonator must be controlled in the manner described hereinabove for the index-modulated slab waveguide. In addition to the 2D waveguide material and the substrate material, the transverse geometry of the 2D waveguide must also be chosen to yield the desired spatial overlap and phase match/mismatch properties.

The modal index of index-modulated slab waveguide 132 or 2D waveguide 134 may be controlled by electronic, optical, and/or other means. For example, a quantum well, multi-quantum well (MQW), other semi-conductor, or any other suitable electro-optic material may be incorporated into the modulator waveguide as an electro-optic material, so that the modal index of the modulator waveguide may be altered by application of a control electric field. For wavelengths between about 1.2 μm and 1.7 μm, the InGaAsP MQW material described in detail hereinabove may be used as a suitable electro-optic material, with the modal index shifted by application of a control electric field through QCSE, FKE, QCFKE, or other similar mechanism. The properties of the MQW material must differ slightly depending on whether the material is to be used as an electro-absorptive material or an electro-refractive material. In both cases the bandgap of the barrier layers should preferably be substantially greater than the photon energy of the light to be modulated. For an electro-absorptive material, however, the quantum well bandgap should be between about 30 meV and about 60 meV above the photon energy (in contrast to 10-30 meV for an electro-absorptive material), so that the modulator waveguide does not introduce unwanted optical loss. A modulator control element may comprise control electrodes suitably positioned to apply the control electric field. Alternatively, the modal index of such materials may be controlled by injection of current into the material. The presence of additional charge carriers (electrons or holes, as the case may be) may serve to increase or decrease the modal index of the waveguide material, depending on the bandgap, band structure, and/or doping of the semiconductor and the wavelength of the optical mode to be modulated. Control electrodes or other electrical contact may serve to inject a control electrical current. Optical excitation of such materials may also serve to generate charge carriers, thereby allowing control of the waveguide modal index to be controlled by application of an optical control signal.

Other classes of materials exhibiting non-linear optical polarizability, saturable optical polarizability, non-linear Kerr effect, and/or other non-linear optical responses may be equivalently incorporated into the modulator waveguide to enable control of the waveguide modal index by application of an optical control signal. As with the loss-modulated embodiments, many other electro-optic materials or material combinations may be employed to implement an index-modulated embodiment operable at other wavelengths. Several suitable material combinations are disclosed in earlier-cited application A7.

An index-modulated embodiment of an optical power control device according to the present invention is shown in Figs. 4A and 4B in which the modulator optical element comprises an open arcuate modulator optical waveguide 138 positioned axially with respect to the WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-cited application A5. Other WGM resonator structures could be equivalently employed. In Fig. 4A spacer 139 is shown for positioning arcuate waveguide 138 at the proper distance from WGM resonator 120. In this particular embodiment the spacer 139 comprises a portion of an adjacent fiber segment connected to the fiber-ring resonator with arcuate waveguide 138 deposited thereon, bonded thereto, or otherwise held in contact therewith. Some experimentation will typically be required to determine the spacing between WGM resonator 120 and arcuate waveguide 138 that produces the desired level of round-trip optical loss for WGM resonator 120 and the appropriate phase matching conditions between WGM resonator 120 and arcuate waveguide 138. Once the proper thickness of spacer 139 has been determined, it may be reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, or other suitable processing of the adjacent fiber segment. A similar spacer may be employed for other types of WGM resonator as well. The same types of materials used for the index-modulated slab and 2D waveguides described hereinabove may be employed for fabricating index-modulated arcuate waveguide 138. In particular, arcuate waveguide 138 may comprise the InGaAsP multi-quantum well material described hereinabove, with the alternating quantum well and barrier layers substantially parallel to WGM resonator 120 and with the control electric field

applied substantially perpendicular to WGM resonator 120. An advantage of this embodiment is increased interaction length between the whispering-gallery optical mode and the arcuate waveguide relative to the tangentially positioned waveguides, therefore requiring smaller modal index shifts to achieve the same changes in power transfer through evanescent optical coupling to and round trip optical loss from the WGM resonator.

A significant property of both tangentially- and axially-positioned index-modulated open modulator optical waveguide structures is that since no re-circulation of any waveguide optical mode occurs, the presence of the modulator optical waveguide has a substantially negligible effect on the wavelength-dependent properties and/or resonant behavior of the adjacent WGM optical resonator. Such wavelength/frequency shifting behavior can adversely affect the performance of an optical power control device according to the present invention, or alternatively may be exploited to enhance said performance, depending on the design, construction, and use of a particular device.

Various index-modulated embodiments of an optical power control device according to the present invention are shown schematically in Figs. 5A through 5E in which the modulator optical element comprises a closed optical waveguide (i.e., a modulator optical resonator 140) positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with respect to the WGM resonator 120, and oriented substantially parallel to (Figs. 5A, 5C, and 5D) or substantially perpendicular to (Figs. 5B and 5E) the WGM resonator 120. Transmission waveguide 110 is shown as a tapered fiber-optic waveguide. A fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM optical resonator is shown as a micro-disk or micro-ring resonator. Other WGM resonator structures could be equivalently employed. Index-modulated modulator optical resonator 140 may comprise any of the resonator structures recited earlier for WGM resonator 120, including but not limited to spheres, near-spheres, oblate and/or prolate spheroids, ovals, ovoids, racetracks, ellipsoids, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A7), ring or other closed waveguides, and/or functional equivalents thereof, and are shown generically as micro-disks or micro-rings in Figs. 5A through 5E. Index-modulated modulator optical

resonator 140 is shown in Figs. 5A and 5B in substantial tangential engagement with WGM optical resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical mode extending radially beyond WGM resonator 120 may overlap a portion of modulator optical resonator 140, either a radially-extending portion thereof when substantially parallel to WGM resonator 120 (Fig. 5A), or an axially-extending portion thereof when substantially perpendicular to WGM resonator 120 (Fig. 5B). Index-modulated modulator optical resonator 140 is shown in Figs. 5C, 5D, and 5E positioned axially with respect to WGM optical resonator 120, either in direct mechanical contact, or positioned at a specific distance from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical mode extending axially beyond WGM resonator 120 may overlap a portion of modulator optical resonator 140, either an axially-extending portion thereof when substantially parallel to WGM resonator 120 (Figs. 5C and 5D), or a radially-extending portion thereof when substantially perpendicular to WGM resonator 120 (Fig. 5E).

Index-modulated modulator optical resonator 140 may preferably be fabricated incorporating an electro-optic material, so that the modal index of a modulator resonator optical mode may be controlled by a modulator control element. The modulator optical resonator 140 should preferably have a resonant optical mode having substantially the same wavelength as the whispering-gallery optical mode of WGM resonator 120 (and hence the propagating optical mode to be controlled). This enables transfer of optical power from the WGM resonator and build-up of optical power within the modulator optical resonator, in turn enabling dissipation of optical power from modulator resonator 140 to produce sufficiently large round trip optical loss for the WGM resonator 120 coupled thereto. If the modulator optical resonator and WGM optical resonator are not resonant with each other, in contrast, the modulator resonator would have a negligible effect on the round-trip loss of the WGM resonator. Index-modulated modulator optical resonator 140 may preferably be fabricated incorporating an electro-optic material, so that the modal index of a modulator resonator optical mode may be controlled by a modulator control element. A complication encountered when implementing an embodiment

that includes an index-modulated modulator resonator arises from the unavoidable wavelength shift of the resonant optical mode of the modulator resonator that occurs with a change in the modal index thereof. The WGM resonator and modulator optical resonator must be treated as a coupled-cavity system, and shifts in the modulator resonance wavelength may perturb the resonances of the coupled system. This effect must be properly accounted for in designing an optical power control device incorporating a modulator optical resonator, or alternatively, the effect may be exploited for designing optical power control devices with specific wavelength dependent performance characteristics. One approach might involve providing the modulator resonator with two index-modulated regions: one at the interaction region near the WGM resonator and another far from the WGM resonator. Application of a control signal may serve to change the modal index in the interaction region to change the level of optical power transfer by evanescent optical coupling, while the modal index in the second region may change by an appropriate amount to leave the resonance frequency of the modulator resonator substantially unchanged. The effects of shifting resonances in the coupled-cavity system may be somewhat mitigated for a low-Q index-modulated resonator modulator element, since the dissipation of optical power from the modulator resonator tends increase the bandwidth of its resonances, in turn decreasing the effect of the modulator resonances on the WGM resonances in the coupled-cavity system. In short, index- or coupling-modulated resonators or "closed waveguide" modulator optical elements having relatively low finesse (less than about 10) may behave substantially less "resonator-like" than the relatively high-finesse WGM resonator.

Alternatively, the modulator optical resonator 140 may be a relatively high-Q resonator and should preferably have a resonant optical mode having substantially the same wavelength as the whispering-gallery optical mode of WGM resonator 120 (and hence the propagating optical mode to be controlled). Transfer of optical power from the whispering-gallery optical mode of WGM resonator 120 into modulator optical resonator 140, and subsequent dissipation of optical power therefrom, may be modulated (to a degree sufficient to switch the optical power control device between conditions of under- and critical-coupling, or between conditions of critical- and over-coupling) by modulation of the modal index of the modulator resonator 140 to shift the resonance wavelength thereof from a condition of resonance with the whispering-gallery optical mode (yielding greater optical power transfer to the modulator optical mode) to a condition of

non-resonance with the whispering-gallery optical mode (yielding little or no optical power transfer to the modulator optical mode). Dissipation of optical power from the modulator resonator 140 in such a "resonance-modulated" device may be achieved in a variety of ways. The dissipated optical power may be allowed to simply propagate in the modulator resonator away from the interaction region to radiate into the environment, without an opportunity to couple back into the WGM resonator. Alternatively, the modulator resonator may be provided with a region of high optical loss (which need not be modulated). The high-loss region may encompass all or a portion of the modulator resonator, and may or may not be spatially separate from the interaction region. The optical loss may be provided in myriad functionally equivalent ways, including but not limited to optical absorption and optical scattering, and optical power coupled into the modulator resonator from the WGM resonator may propagate in the region of high optical loss and be absorbed or otherwise dissipated. Any functionally equivalent means for dissipating optical power transferred into the modulator resonator from the WGM optical resonator may be employed without departing from inventive concepts disclosed and/or claimed herein.

Any of the electro-optic materials recited hereinabove for an index-modulated modulator waveguide, or functional equivalents thereof, may be incorporated into a modulator resonator according to the present invention, with suitable adjustment to yield electro-refractive behavior instead of electro-absorptive behavior. An index- or resonance-modulated modulator optical resonator may be positioned relative to a WGM fiber-ring resonator by a spacer as shown in Figs. 6A-6C, Fig. 7, and Figs. 8A-8B.

A preferred material for any of the index-modulated modulator optical waveguides and/or resonators of Figs. 3A-3B, 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 may be a Bragg multi-layer dielectric stack (also referred to as a distributed Bragg reflector, or DBR, stack). Such multi-layer DBR stacks support and/or guide propagation of so-called surface guided optical modes (SGOMs) such as surface-guided Bloch modes (SGBMs), for example. A SGOM supported by any of the index-modulated modulator waveguides and/or modulator resonators of Figs. 3A-3B, 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 (fabricated as a DBR stack) may serve as the modulator optical mode. The surface-guided modulator optical mode may be evanescently optically coupled to the whispering-gallery optical mode from the top of the Bragg stack (referred to as

"surface-coupled"), or from the side of the Bragg stack (referred to a "side-coupled"). The Bragg stack is preferably fabricated (typically using epitaxial, evaporative, effusive, and/or chemical vapor deposition/growth techniques, wafer-bonding techniques, and/or other related techniques) incorporating an electro-optic layer and control electrodes for applying a control electric field to control the material index of the electro-optic layer. The strongly dispersive optical properties of a DBR-guided SGOM (a substantially flat dispersion relation in the operating wavelength range, so that a narrow range of wavelengths cover a wide range of propagation constants or modal indices) serve to produce a substantially larger modal index shift of the SGOM for a given applied control voltage level than previous electro-optic devices. This in turn enables optical power control devices incorporating electro-optic/DBR waveguides or resonators according to the present invention to be operated with substantially smaller control voltages (and lower electrical drive power consumption) than their counterparts incorporating simpler electro-optic materials and/or geometries. A wide variety of material combinations, layer sequences, and/or fabrication/processing techniques may be employed to implement an electro-optic/DBR stack embodiment of the present invention. Many examples of such surface-guiding electro-optic/DBR stack waveguides and/or resonators are disclosed in earlier-cited application A7, and any of those examples may be employed in an index-modulated, surface-coupled modulator, and/or a resonance-modulated, surface-coupled modulator resonator, without departing from inventive concepts disclosed and/or claimed herein.

In an alternative embodiment of any of the index-modulated modulator optical waveguides and/or resonators of Figs. 3A-3B, 5A, and/or 5E, a pair of DBR stacks may be employed surrounding a core layer. In such structures the modulator optical mode may be supported and substantially confined by the Bragg stacks in a region near the core layer. The confined modulator optical mode may be evanescently optically coupled to the whispering-gallery optical mode from the side of the Bragg stack ("side-coupled"). The Bragg stack is preferably fabricated (typically using epitaxial, evaporative, effusive, and/or chemical vapor deposition/growth techniques, wafer-bonding techniques, and/or other related techniques) incorporating an electro-optic layer and control electrodes for applying a control electric field to control the material index of the electro-optic layer. The strongly dispersive optical properties of a dual-DBR-guided confined optical mode enable operation of devices with substantially smaller

control voltages (and lower electrical drive power consumption) than their counterparts incorporating simpler electro-optic materials and/or geometries, in a manner analogous to that described hereinabove for SGOMs. Many examples of such electro-optic/dual-DBR stack waveguides and/or resonators are disclosed in earlier-cited application A7,and any of those examples may be employed in an index-modulated, side-coupled modulator, and/or a resonance-modulated, side-coupled modulator resonator, without departing from inventive concepts disclosed and/or claimed herein.

Exemplary fabrication procedures and cross-sectional structures of index-modulated electro-optic/Bragg stack waveguides or resonators are depicted in Figs. 9 through 16. The flowchart of Fig. 9 and process diagram of Fig. 10 illustrate fabrication (by epitaxial techniques and/or other functionally equivalent deposition/growth/processing techniques) of a Bragg multi-layer dielectric stack 2202 and a high-index core layer 2204 on a first substrate 2210, the Bragg stack comprising alternating $\lambda/4$ (quarter-wave) layers of materials differing in material refractive index. A preferred Bragg stack may comprise alternating $\lambda/4$ layers of GaAs (index about 3.5) and high-aluminum-fraction AlGaAs (between about 0.90 and about 0.97 aluminum; index about 3.2) on a GaAs substrate. In general the appropriate quarter-wave thickness is determined based on the index of the material ultimately present in a given layer; this may not be the same material initially deposited if subsequent processing (oxidation, for example) brings about a chemical conversion of the layer to a new material. A doped layer 2220 of InGaAs may be provided between the substrate 2210 and the Bragg stack 2202 to enable subsequent electrical contact for applying the control voltage, and a GaAs or AlGaAs cladding layer may be provided on top of the Bragg stack if desired.

On a second substrate 2240, a MQW material electro-optic layer 2208 may be fabricated (for example, the InGaAsP MQW material as described hereinabove for use as an electro-absorptive or electro-optic material for wavelengths from about 1.2 μm to about 1.7 μm; other functionally equivalent electro-optic materials may be used) and may include cladding layers above and below the MQW layers (if desired) and a doped layer 2230 between the MQW layer 2208 and the substrate 2240 to enable subsequent electrical contact for applying the control voltage. The top of the MQW material 2208 (or the top cladding layer, if present) is then wafer-bonded or equivalently secured to the high-index core layer 2204 (or top cladding layer, if

present) on the Bragg stack 2202. The MQW substrate 2240 may then be etched away or otherwise equivalently removed, leaving the MQW electro-optic layer 2208, contact layer 2230, and bottom cladding layer (if present) exposed and accessible for subsequent evanescent optical surface coupling to the WGM optical resonator. Use of wafer-bonding techniques in this example is required due to the lattice mismatch between the GaAs/AlGaAs DBR stack and the InGaAsP MQW. If lattice-compatible materials are employed for the DBR and the electro-optic layer, then both may be deposited sequentially on a single substrate, and no wafer-bonding step is required. Numerous examples of DBR and electro-optic material combinations, some requiring wafer-bonding and others fabricated on a single substrate, are disclosed in earlier-cited application A7.

The wafer-bonded Bragg stack/MQW composite structure 2250 is then spatially-selectively etched (using etch mask 2270, for example) and/or otherwise processed to leave a protruding ridge structure of the appropriate shape (a straight or arcuate segment 2252 for an open waveguide as in Fig. 11; a ring, racetrack, or other closed path for a closed waveguide or resonator 2254 as in Fig. 12) on substrate 2210. As shown in cross-section in Figs. 13 and 14, ridge structure 4300 may be oxidized, converting lateral portions 4332 of each AlGaAs layer 4330 to aluminum oxide and leaving a central portion 4334 of AlGaAs in each of the AlGaAs layers 4330. These central AlGaAs portions 4334 together with GaAs layers 4320 form a core of the waveguide (or resonator) structure 4300, while the lateral aluminum oxide portions 4332 together form lateral cladding layers of the waveguide (or resonator) structure 4300. The aluminum fraction of each of the AlGaAs layers may be the same, yielding a waveguide (or resonator) core of substantially uniform width upon lateral oxidation (Fig. 13), or the aluminum fraction may decrease from the bottom of the Bragg stack near the substrate up towards the top of the stack, yielding a waveguide (or resonator) core that is narrower at the bottom of the Bragg stack near the substrate and that becomes wider toward the top of the stack upon lateral oxidation (Fig. 14). Oxidation proceeds more rapidly with increasing Al content of a given layer.

The MQW material acts as an electro-optic spacer on the Bragg stack waveguide (or resonator), and application of the control voltage across the doped contact layers changes the material index of the MQW. This in turn results in substantially larger changes in the modal index of the SGOM supported by the Bragg stack, and therefore substantial shifts in the phase

matching condition (and degree of optical power transfer between under-, critical-, and/or over-coupling) between the Bragg stack and the WGM resonator. Larger changes in the level of optical power transfer may be achieved for a given applied control voltage using an electro-optic/Bragg stack device than by using a simple electro-optic device as described earlier herein, enabling substantial reduction of control voltage and electrical drive power to operate an optical power control device. While Bragg multi-layer dielectric stacks fabricated from GaAs/AlGaAs are currently preferred (since they are already well-understood and well-characterized and yield high-index-contrast DBR structures), other combinations of materials yielding functionally equivalent Bragg stacks (currently known or hereafter developed) may be employed without departing from inventive concepts disclosed and/or claimed herein. Similarly, while InGaAsP multi-quantum well materials are currently preferred (since they are already well-understood and well-characterized, and are suitable for use in the technologically important 1.2-1.7 μm wavelength range), other multi-quantum well materials yielding functionally equivalent electro-optic properties (currently known or hereafter developed) may be employed without departing from inventive concepts disclosed and/or claimed herein. Alternatively, any of the electro-optic materials disclosed hereinabove may be equivalently employed for fabricating an electro-optic spacer in conjunction with a Bragg stack as disclosed herein.

The flowchart of Fig. 15 and the fabrication process diagram of Fig. 16 illustrate fabrication (by epitaxial and/or other functionally equivalent growth/deposition/processing techniques) of a Bragg multi-layer dielectric stack 2002 and high-index core layer 2004 on a substrate 2010. At least one layer of the Bragg stack 2002 is an electro-optic material layer. An exemplary Bragg stack of this type may comprise alternating $\lambda/4$ layers of high-aluminum-fraction AlGaAs and GaAs/InGaAs MQW material on a GaAs substrate, and may include top and bottom doped InGaAs contact layers 2020 and 2030 and a top GaAs cladding layer. The Bragg stack 2002 is processed (by lithography or other functionally equivalent technique) to form a ridge structure and laterally oxidized as described hereinabove, yielding a central core and lateral cladding for the waveguide (or resonator) structure, which may be evanescently optically surface-coupled to the WGM optical resonator. Application of a control voltage across the contact layers 2020 and 2030 results in a shift of the material index of the GaAs/InGaAs MQW material, substantially larger shifts in the modal index of the SGOM, and substantial shifts

in the phase matching condition (and degree of optical power transfer between under-, critical-, and/or over-coupling) between the Bragg stack waveguide and the WGM resonator. GaAs/InGaAs MQW material is not ideally suited for modulating optical wavelengths typically used in long-haul fiber-optic telecommunications (between about 1.2 mm and about 1.7 mm), but rather better suited for the 0.7-0.8 μm region (often utilized for so-called metro, or short-haul fiber-optic telecommunications networks). Bragg stacks incorporating any suitable MQW materials or other electro-optic materials (including InGaAsP MQW material, suitable for typical fiber-optic telecommunications wavelengths), currently known or hereafter developed, may be equivalently employed without departing from inventive concepts disclosed and/or claimed herein. Suitable combinations of materials will typically be determined by lattice-compatibility, bandgap, operating wavelength, and so on.

Any of the electro-optic/Bragg stack structures described hereinabove and/or disclosed in earlier-cited application A7 may be used to fabricated a resonance-modulated modulator optical resonator, wherein the modal index shift of the applied control voltage functions to shift the resonance wavelength of the modulator optical mode (SGOM in this case) into and out of resonance with the whispering-gallery optical mode. The shifting of the resonance wavelength of the modulator resonator serves to switch the level of optical power transfer from the WGM resonator between under-, critical-, and/or over-coupling, as described hereinabove.

As a further generalization of resonant optical power control devices according to the present invention, the WGM resonator may comprise a Bragg stack structure fabricated in a manner analogous to the fabrication procedures described herein and in earlier-cited application A7. Such a WGM optical resonator may comprise a single Bragg stack structure supporting a surface-guided resonant optical mode, and evanescent optical coupling between the WGM resonator and the transmission waveguide and between the WGM resonator and the modulator optical element may occur through an axially-extending evanescent portion of the surface-guided optical mode of the WGM resonator. Alternatively, the WGM optical resonator may comprise a dual Bragg stack structure substantially confining a resonant optical mode therebetween, and evanescent optical coupling between the WGM resonator and the transmission waveguide and between the WGM resonator and the modulator optical element may occur through a radially-extending evanescent portion of the confined optical mode of the WGM resonator.

In order to achieve and maintain reliable, reproducible, and stable evanescent optical coupling between a transmission optical waveguide, a WGM resonator, and a modulator optical element during and after manufacture of a resonant optical power control device according to the present invention, an alignment device may be employed, as illustrated by the exemplary assemblies of Figs. 17A-17C, 18A-18C, 19A-19B, 20A-20B, 21A-21B, 22A-22B, 23A-23B, and 24A-24B. Such an alignment device may comprise a first alignment substrate 502 having a transmission-waveguide-alignment groove 506 thereon, and various embodiments are described in detail in earlier-cited applications A4 and A5. Alignment substrate 502 may be further provided with a WGM-resonator-alignment groove 504, or groove 504 may be provided on a second alignment substrate 702. A method for fabricating a resonant optical power control device according to the present invention comprises the steps of: 1) positioning and securing a transmission fiber-optic waveguide within the transmission-waveguide-alignment groove 506; and 2) positioning and securing the WGM optical resonator within the resonator-alignment groove 504 (as shown, for example, in Figs 17A-17C and 18A-18C for the case when grooves 504 and 506 are both provided on substrate 502). The transmission fiber-optic- waveguide may comprise a fiber taper 600, an optical fiber 300 with a saddle-shaped evanescent optical coupling segment, or any other functionally equivalent transmission optical waveguide having an evanescent coupling segment. The WGM resonator may comprise a microsphere 620 connected to a neck portion 622 of a microsphere fiber segment 624, a fiber-ring 602 connected to adjacent fiber segments 604, or any other functionally equivalent WGM resonator structure. Notwithstanding the exemplary combinations shown in the Figures, any suitable WGM resonator may be combined with any suitable transmission fiber-optic waveguide to yield a resonant optical power control device according to the present invention. The transmission-waveguide-alignment groove 506 may be positioned on the alignment substrate 502, and resonator-alignment groove 504 may be positioned on the alignment substrate 502 or 702, so that when positioned and secured therein (and substrates 502 and 702 are assembled, if groove 504 is provided on substrate 702), the transmission fiber-optic waveguide and the WGM resonator are in substantial tangential engagement (usually mechanical contact between the waveguide and the circumference of the resonator), thereby evanescently optically coupling the WGM resonator to the transmission fiber-optic waveguide. Optical coupling between the WGM resonator and the

transmission fiber-optic waveguide may be achieved as long as at least portion of an evanescent portion of one of the whispering-gallery optical mode of the resonator and a propagating optical mode of the transmission fiber-optic waveguide spatially overlaps at least a portion of the other optical mode. Actual mechanical contact is not required, only that the resonator and fiber be sufficiently close to permit the overlap. However, in a preferred embodiment of an optical power control device according to the present invention, optical coupling between the resonator and the fiber may be most reproducibly, reliably, and stably achieved by positioning and securing the WGM resonator and the transmission fiber-optic waveguide in mechanical contact with one another.

The second alignment substrate 702 of the alignment device may also have the modulator optical element secured thereto or mounted thereon. Alignment substrate 702 (and/or alignment substrate 502, if groove 504 is provided thereon) may be suitably mechanically indexed or otherwise provided with means for reliably, reproducibly, and stably positioning the modulator optical element for evanescent optical coupling to the WGM optical resonator (either in direct mechanical contact or a space therebetween). The alignment grooves 504 and 506, and any indexing or other alignment means, together serve to suitably position the modulator optical element, WGM resonator, and transmission fiber-optic waveguide relative to each other, when all are secured to the assembled alignment device.

Similar alignment structures may be employed whether the modulator optical element is a waveguide or resonator, and whether the modulator optical element is loss-modulated, index-modulated, resonance-modulated, or interference-modulated. Exemplary assemblies include: slab modulator waveguide 132 shown in Figs. 19A-19B (with groove 504 on substrate 502); 2D modulator waveguide 134 on substrate 136 shown in Figs. 20A-20B (with groove 504 on substrate 502); modulator resonator 140 (side-coupled, as in Fig. 5A) shown in Figs. 21A-21B (with groove 504 on substrate 502); ridge modulator waveguide 2252 (surface-coupled) shown in Figs. 22A-22B (with groove 504 on substrate 702); ridge modulator waveguide 2252 (side-coupled) shown in Figs. 23A-23B (with groove 504 on substrate 702); and ridge modulator resonator 2254 (surface- coupled, as in Fig. 5B) shown in Figs. 24A-24B (with groove 504 on substrate 702). The embodiment of Figs. 24A-24B may be modified to provide sidee-coupling between modulator resonator 2254 and fiber-ring resonator 602 (as in Fig. 5E).

The present invention has been set forth in the forms of its preferred and alternative embodiments. It is nevertheless intended that modifications to the disclosed modulators for optical power control devices, and methods of fabrication and use thereof, may be made without departing from inventive concepts disclosed and/or claimed herein.